

Metamorphic solid salt (KCl-NaCl) in quartzo-feldspathic polyphase inclusions in the Sulu ultrahigh-pressure eclogite

ZENG LingSen^{1*}, CHEN ZhenYu² & CHEN Jing³

¹ State Key Laboratory of Continental Tectonics and Dynamics, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China;

² Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China;

³ School of Physics, Peking University, Beijing 100871, China

Received March 13, 2012; accepted May 31, 2012; published online October 18, 2012

Unusual polyphase inclusions of K-feldspar + quartz + titanite + solid salt and K-feldspar + albite + quartz + epidote with textures similar to the other K-feldspar + quartz inclusions were found in omphacite grains from the Sulu ultrahigh pressure (UHP) eclogites. One of these inclusions contain square to round solid salt inclusions of KCl-NaCl composition. Such a mineral assemblage within K-feldspar-bearing inclusions hosted by UHP metamorphic phases suggests that (1) potassium granitic melts enriched in Cl components were presented during UHP metamorphism or at the early stage of rapid exhumation of deeply subducted continental slab; (2) they were resulted from reactions between the incoming granitic melts and quartz (or coesite); and (3) solid salt inclusions of NaCl-KCl were derived from dehydration and desiccation of Cl-bearing melts. Our new observations further demonstrate that during the tectonic evolution of UHP rocks, fertile components within deeply subducted continental materials could undergo partial melting, leading to the formation of Cl-bearing potassium granitic melts and substantial migration of fluid-conservative elements (e.g. Ti, Hf) within the UHP slab.

quartzo-feldspathic polyphase inclusions, solid salt inclusion, eclogite, ultrahigh-pressure metamorphism, Sulu UHP belt

Citation: Zeng L S, Chen Z Y, Chen J. Metamorphic solid salt (KCl-NaCl) in quartzo-feldspathic polyphase inclusions in the Sulu ultrahigh-pressure eclogite. *Chin Sci Bull*, 2013, 58: 931–937, doi: 10.1007/s11434-012-5373-y

A number of studies have demonstrated that continental crustal materials could be subducted to depths greater than 100 km [1,2] and accompanied by limited dehydration [3] and pronounced oxidization [4,5]. Fertile components within the rocks that had been subjected to ultrahigh-pressure (UHP) metamorphism could experience partial melting [6–15] and produce granitic melts and even supercritical fluids [16] during the deep subduction or the early stage of rapid exhumation of continental slab. Under pressures high enough to surpass the second critical termination point, fluids and hydrous melts could mix completely and form homogenous supercritical fluids [17,18]. Such fluids, geochemically similar to granitic melts, could dissolve not only a large quantity of large lithophile elements (LILE) and rare earth elements (REE), but also normally fluid-immobile elements such as

high field strength elements (HFSE), and become an excellent medium to transport these elements. During the tectonic evolution of continental subduction zones, formation and migration of granitic melts or supercritical fluids not only affect the geochemical properties of the subducted continental slab itself, but also exert strong influences on the physical and chemical properties of the overlying slab. Therefore, identification whether the deeply subducted continental material experienced partial melting and whether supercritical fluids presented is one of the frontiers of recent UHP studies [16]. Resolving these issues will promote our understanding and appreciation of the pronounced physical and chemical effects of deep subduction and associated UHP metamorphic reactions of continental materials.

The geochemical nature of fluids associated with UHP metamorphism is commonly inferred from fluid inclusions in UHP phases. High salinity fluid inclusions have been

*Corresponding author (email: changting1970@yahoo.com)

reported in garnet as well as omphacite in UHP rocks. Fluid inclusions hosted by UHP minerals in the Dabie-Sulu orogenic belt consist mainly of $\text{H}_2\text{O} \pm \text{CO}_2$, and intermediate to low salinity $\text{H}_2\text{O}-\text{CO}_2$ fluids were presented at prograde, peak, and retrograde metamorphic stages [19–23]. Furthermore, high salinity fluids of $\text{NaCl}-\text{CaCl}_2-\text{H}_2\text{O}$ composition also existed at least locally under UHP conditions [19,21–23]. Factors that control the chemical composition and salinity of such fluid inclusions include their sources as well as the hosted mineral-fluid re-equilibration [3,24]. Presence of anomalous high salinity fluids within the UHP rocks implies that local hosted mineral-fluid re-equilibration could be a dominated factor that regulates the composition of UHP metamorphic fluids [22]. However, the origin of anomalous high salinity fluids in UHP eclogites is still an unresolved issue. Interestingly, recent experiments had shown that the solubility of rutile in Cl-bearing fluids is 2–4 times higher than that in pure water, indicating that Ti mobility in Cl-bearing aqueous fluids is substantially higher than expected [25]. Therefore, identification of high salinity fluids in UHP rocks and resolving their origin could not only help to understand the kinetic behavior of key accessory minerals (e.g. apatite, rutile, and zircon) under UHP metamorphic conditions, but also help to constrain the composition and state of deep metamorphic fluids, dehydration or degassing processes of fluids or melts, and their effects on tectonophysical properties of deep crustal rocks.

Recent studies have documented a number of quartzo-feldspathic polyphase inclusions consisting of K-feldspar, albite, and quartz hosted by garnet as well as omphacite in the Dabie-Sulu UHP eclogites [5,26–28]. Presence of these extraordinary inclusions in UHP rocks implies that the Dabie-Sulu UHP rocks might have experienced partial melting [27,28] during UHP metamorphism. In order to further constrain the chemical properties of these melts, detailed examinations show that except for barite identified previously, these polyphase inclusions also contain square or round solid salt of $\text{KCl}+\text{NaCl}$ composition and irregular titanite (CaTiSiO_5). Co-existence of solid salt, barite, and titanite in quartzo-feldspathic polyphase inclusions suggests that hydrous, sulfate- and Cl-bearing melts were involved in melt-quartz (coesite) or -omphacite reactions and produced supercritical fluids, an excellent medium for large-scale transportation of HFSE, under UHP conditions.

1 Sample descriptions

Sample CCSD-02 of this study was collected in an eclogite quarry ($118^\circ40'27''\text{E}$, $34^\circ24'01''\text{N}$) close to the main borehole of Chinese Continental Scientific Drilling Project (CCSD) located to the Maobei of Donghai, Jiangsu Province. To better characterized the composition and texture of the constituent phases and inclusions, thin sections were prepared along directions parallel, perpendicular, and

oblique to the stretching lineation of this sample. Sample CCSD-02 is a relatively fresh rutile eclogite with well-developed foliation and stretching lineation and consists of garnet, omphacite, rutile, phengite, and minor apatite (Figure 1(a)). It had experienced weak retrograde reactions as represented by the hornblende + plagioclase symplectite along the grain boundaries of garnet and omphacite or along the micro-fractures within garnet or omphacite. However, no titanite was found either around rutile or within the symplectite, which indicates that rutiles had not experienced retrograde reactions. Apatite contains a large amount of oriented sulfide consisting dominantly of FeS and minor FeS_2 , similar to those from other Sulu eclogites [29,30]. Other than epidote and titanite as part of the quartzo-feldspathic inclusions, both phases do not present neither in the constituent phases nor in the retrograde symplectites. Several K-feldspar-bearing polyphase inclusions were identified within garnet as well as omphacite. These inclusions are commonly euhedral to subhedral (Figure 1(b)–(d)) and some of them are surrounded by outward growing radial fractures (Figures 1(b) and 2(c)). Among these inclusions, one of them contains a number of micron size ($<10\text{ }\mu\text{m}$) solid salt (Figure 2(d) and (e)), whereas irregular titanite grains occur along the grain boundaries of K-feldspar and quartz in three (MS-2, -3 and -4) inclusions (Figure 2).

2 Analytical methods

The texture and mineral compositions of these inclusions

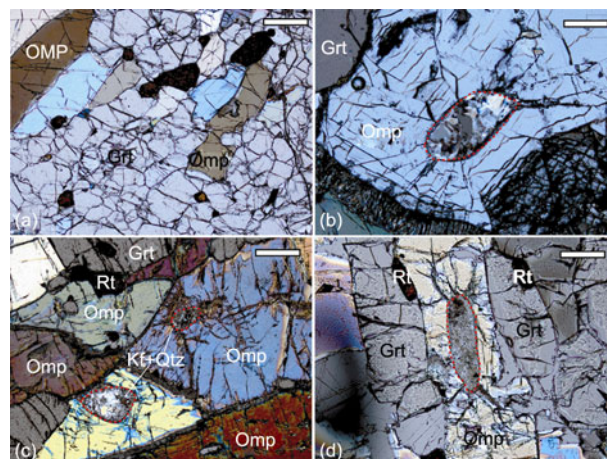


Figure 1 Microphotographs showing the texture and mineral assemblage in eclogite sample CCSD-02 and K-feldspar-bearing polyphase inclusions hosted by omphacite. (a) Overall view of the texture of mineral assemblage in sample CCSD-01. It consists of garnet, omphacite, phengite, and rutile. Rutile grains are distributed mainly along the grain boundaries of garnet and omphacite. Omphacite grains show preferential orientation. (b) K-feldspar + Albite + Epidote + Quartz polyphase inclusion in omphacite. This inclusion is surrounded by well-developed radial fractures that are limited within the host omphacite. (c) Two K-feldspar + Quartz inclusions in omphacite. (d) Prismatic and subhedral inclusion of K-feldspar + Quartz + Titanite + solid salt in omphacite. Scale bars=200 μm . Omp, omphacite; Grt, garnet; Rt, rutile; Qtz, quartz; Kf, K-feldspar; Ab, albite.

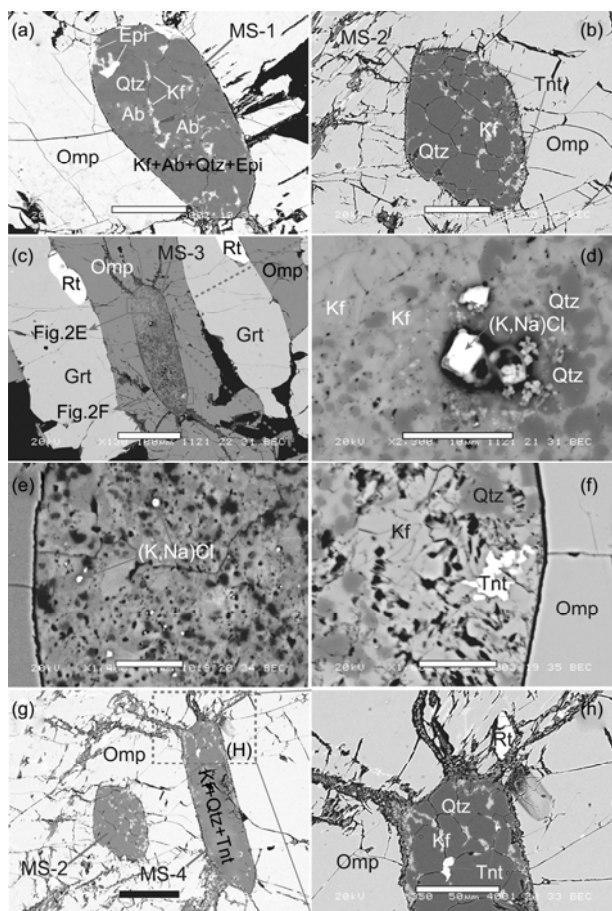


Figure 2 Back Scatter Electronic (BSE) images showing the texture and mineral compositions of Kf-bearing polyphase inclusions. (a) MS-1: K-feldspar + Albite + Epidote + Quartz polyphase inclusion in omphacite. K-feldspar occurs mainly along the grain boundaries of albite, quartz, and epidote. Scale bar = 100 μm . (b) MS-2: polyphase inclusion of K-feldspar, quartz, and titanite with a pseudomorph after coesite in omphacite. Irregular K-feldspar distributes along the grain boundaries of quartz grains. Titanite grains (white phases) occur in the upper right and lower right of this inclusion. Scale bar = 100 μm . (c) MS-3: K-feldspar + Quartz + Titanite + Solid Salt inclusion in omphacite. Quartz and K-feldspar show mosaic intergrowth texture. Titanite occurs in the lower right of this inclusion. Scale bar = 200 μm . (d) Enlarged view of the inclusion MS-3 showing the occurrence and texture of solid salt. Scale bar = 20 μm . (e) Enlarged view of the inclusion MS-3 showing the occurrence and texture of round micron-size solid salt. Scale bar = 20 μm . (f) Enlarged view of the inclusion MS-3 showing the occurrence and texture of titanite. Scale bar = 20 μm . (g) Two K-feldspar-bearing inclusions (MS-2 and MS-4) in the same omphacite. Scale bar = 200 μm . (h) Enlarged view of the inclusion MS-4 showing the texture of coexisting quartz, K-feldspar, and titanite. Scale bar = 100 μm . Omp, omphacite; Grt, garnet; Qtz, quartz; Ab, albite; Kf, K-feldspar; Rt, rutile; Tnt, titanite; Epi, epidote.

were examined by a Scanning Electron Microscope (SEM). Back scatter electron (BSE) images were obtained by using a JSM-5610LV scanning electron microscope equipped with an energy dispersive X-ray spectrometer (EDS) at the Institute of Geology, Chinese Academy of Geological Sciences. EDS line scan and X-ray composition mapping were also performed with the same instrument. Operating conditions were 20 kV accelerating voltage, beam current 2.8 nA.

Image analysis of high-resolution BSE images of the Kf-bearing inclusions were used to estimate the modal proportions of constituent phases in each inclusion by point counting. During the analysis, spot size is $40\text{ nm}\pm$, spatial resolution is $4\text{ }\mu\text{m}\pm$, but the actual area for analysis is larger than $5\text{ }\mu\text{m}$. Therefore, for those phase with a grain sizes less than $5\text{ }\mu\text{m}$, the final analytical results requires matrix correction.

Chemical Analyses of mineral composition were carried out in the Key Laboratory of Orogenic Belt and Evolution of Continental Crust, the Ministry of Education, Peking University, using a JEOL Super Probe equipped with wavelength dispersive spectrometers. The microprobe was operated with an accelerating voltage of 15 kV, a current of 10 nA, and a spot size of $1\text{ }\mu\text{m}$. Chemical analysis was calibrated with mineral and oxide standards. For the analysis of Na content within both omphacite and albite, a pure albite standard was used to calibrate the potential loss of Na during analysis. Analytical results are listed in Table 1.

3 Data and results

3.1 Characteristics of polyphase inclusions

(1) MS-1: K-feldspar + Albite + Quartz + Epidote inclusion. This inclusion is subhedral and has a clear cut contact with its host omphacite. It consists of quartz, albite, K-feldspar, and epidote. Within this inclusion, quartz dominates and albite, slightly lighter than quartz in the BSE image, occurs mainly in the central part of this inclusion. Epidote occurs at the upper left and upper right corner of this inclusion and coexists with quartz and K-feldspar. K-feldspar occurs along the grain boundaries of quartz grains, quartz and albite or quartz and epidote (Figure 2(a)). It consists of approximately 85% quartz and albite, 10% K-feldspar, and 5% epidote. Similar to other K-feldspar-bearing inclusions, this inclusion also displays off-shoot structures (Figure 2(a)), indicating a fluid state when it was captured.

(2) MS-2: K-feldspar + Quartz + Titanite inclusion. Polyphase inclusions of K-feldspar + quartz are common in the eclogites along the Dabie-Sulu UHP belt [26–28,31]. Such inclusions have been found in garnet as well as in omphacite. Within this sample, some inclusions also contain fine grained anhedral titanite (Figure 2(b)). Inclusion MS-2 displays similar texture to that pseudomorph after coesite. Anhedral K-feldspar occurs along the grain boundaries of quartz. Titanite is located to the upper right and upper left of this inclusion. It consist of ~90% quartz, ~9% K-feldspar, and ~1% titanite.

(3) MS-3: K-feldspar + Quartz + Titanite + Solid Salt inclusion. This inclusion is also hosted by omphacite and consists of approximately equal amount of quartz (~49%), and K-feldspar (~49%), and minor titanite. Quartz and K-feldspar show mosaic intergrowth texture, similar to that

Table 1 Chemical composition of albite (Ab), quartz (Qtz), K-feldspar (Kf), epidote (Epi) and titanite (Tnt) in K-feldspar-bearing inclusions, oxides in wt%^{a)}

Inclusion	MS-1				MS-2			MS-3		
Mineral	Kf	Ab	Epi	Qtz	Kf	Qtz	Tnt	Kf	Qtz	Tnt
No. of analyses	6	5	5	6	6	6	3	6	6	2
SiO ₂	64.79	68.53	38.30	99.33	65.36	99.40	31.22	65.64	98.76	31.24
TiO ₂	0.01	0.03	0.16		0.04	0.01	32.90	0.01		32.96
Al ₂ O ₃	18.06	19.60	28.79		18.19		3.55	18.59	0.03	3.50
FeO	0.01	0.06	4.76	0.06	0.07	0.06	2.47	0.08	0.11	2.52
MnO	0.01	0.01	0.07		0.03			0.05		
MgO			0.20			0.03				
CaO	0.03	0.17	22.09	0.02	0.03	0.01	28.06	0.05	0.03	28.04
Na ₂ O	0.12	11.55	0.01	0.05	0.10		0.10	0.19		0.12
K ₂ O	16.30	0.03		0.01	16.23		0.09	15.43	0.03	0.11
Total	99.33	99.98	94.38	99.46	100.05	99.51	98.39	100.04	98.96	98.49

a) Blank within this table is those oxides below detection limit; values reported in this table are average values based on several analyses shown by the No. of Analyses.

of hornblende + plagioclase symplectite. Within the proximity of this inclusion, there are several relatively large fractures (Figure 1(d)) filled with typical amphibolite facies retrograde assemblage of hornblende, plagioclase, and quartz, but no K-feldspar or other K-bearing phases. A number of blocky or round, micron size KCl-NaCl salt inclusions were preserved within this inclusion (Figure 2(d) and (e)). At the lower right, a ~10 μm big titanite (CaTiSiO_5) occurs near the inclusion boundary (Figure 2(c) and (f)). These fine grained inclusions are distributed along the grain boundaries of K-feldspar, quartz, and albite (Figure 2(d)–(f)). SEM observations show that the solid salt inclusions of KCl-NaCl composition are characterized by well-developed compositional zoning. X-ray composition mapping reveal that this inclusion consists of KCl in the center and NaCl toward the margin (Figure 2(d)).

(4) MS-4: K-feldspar + Quartz + Titanite inclusion. Inclusion MS-4 and MS-2 are hosted by the same omphacite grain (Figure 2(g) and (h)). It is long and prismatic and has similar mineral assemblage and texture to those in MS-2. Titanites in this inclusion are relatively large with sizes of 15 μm and up to 25 μm , and are located well within the interior of this inclusion, and distribute along the grain boundaries of quartz and K-feldspar. Within the proximity of this inclusion, rutile grains in contact with retrograde veinlets had not been converted to titanite, indicating a very low Ti-solubility in the retrograde fluids.

3.2 Mineral chemistry

To further constrain the chemical compositions and internal textures, X-ray compositional mapping was performed on the solid salt-bearing inclusion to determine its element distribution pattern of Si, Al, Na, K, and Cl (Figure 3). In Figure 3, brighter color represents higher concentration of each element, scales are arbitrary and are stretched to maximize contrast for each element. The solid salt inclusions consist mainly of K, Na, and Cl, and display well-developed com-

positional zoning in terms of K and Na (Figure 3(e) and (f)).

For three inclusions (MS-1, -2, and -3) as described as above, we performed EPMA analyses to determine the chemical composition of constituent phases within each inclusion and its host. Analytical results are listed in Table 1.

We selected spots on each phase (albite, K-feldspar, and quartz) large enough to avoid interference from the other phases. EPMA analyses show that: (1) albite grains have relatively uniform composition and contain 68.5 wt% SiO₂,

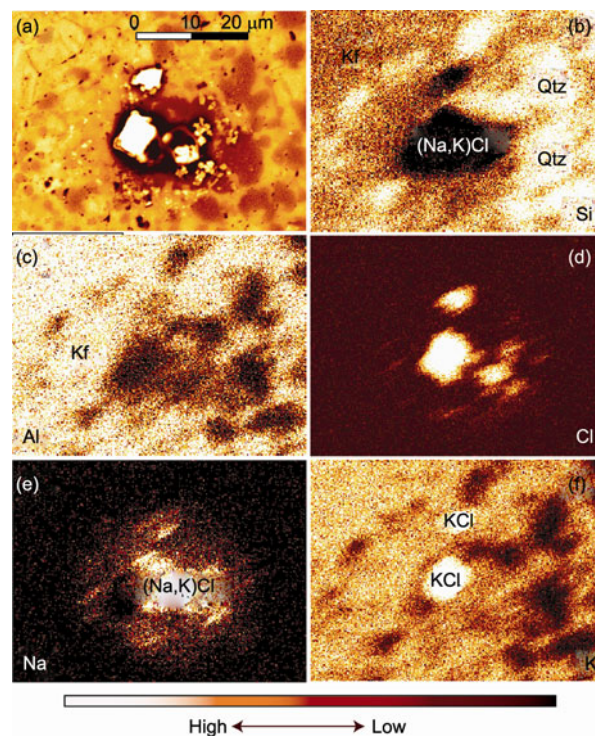


Figure 3 X-ray composition map of solid sylvite (KCl)-halite (NaCl) inclusion within the inclusion MS-3. Co-distribution of K, Na, and Cl indicates the presence of KCl and NaCl within this inclusion. Relative concentrations of Si, Al, Cl, Na, and K are indicated by the lightness of the color. The lighter the color is, the higher the concentration for each element within the inclusion. Kf, K-feldspar; Qtz, quartz.

19.6 wt% Al_2O_3 and 11.6 wt% Na_2O , but low CaO (<0.17 wt%) and K_2O (<0.03 wt%) (Table 1); (2) in all inclusions, K-feldspars have very uniform composition consistent within error with pure KAlSi_3O_8 stoichiometry, with 64.8 wt%–65.6 wt% SiO_2 , 18.1 wt%–18.6 wt% Al_2O_3 , and 15.4 wt%–16.3 wt% K_2O . They also contain tiny amounts of Na_2O , FeO , and TiO_2 (Table 1); (3) quartz grains are nearly pure quartz; and (4) in different inclusions, titanite grains are relatively uniform and consist of ~31.2 wt% SiO_2 , 32.9 wt%–33.0 wt% TiO_2 , and 28.0 wt% CaO with relatively high contents of Al_2O_3 (3.5 wt%–3.6 wt%) and FeO (~2.5 wt%) (Table 1). In order to detect any possible variations in omphacite compositions, careful examination and analyses were carried out on omphacite grains from each sample. Analytical results demonstrate that these omphacite grains have very low K_2O and no substantial variations in Na_2O from the same sample, irrespective of whether they contain K-feldspar-bearing inclusion or not.

4 Discussions

Petrographic examinations show that (1) these inclusions appear to be completely enclosed within optically continuous omphacite grains; (2) each inclusion has a clear-cut boundary with its host; and (3) sample of this study had experienced very minor retrogression. Retrograde metamorphic fluid penetration is limited to the grain boundaries of garnet and omphacite or cracks of the host omphacite. In addition, the composition of these inclusions reported here is completely different from the breakdown products either from garnet or from omphacite. Thus, we believe that these quartzo-feldspathic polyphase inclusions could not be derived from retrograde breakdown of either garnet or omphacite and have retained largely their original bulk compositions.

Available data have demonstrated that major constituent phases in rocks from the interior of the Earth contain silicate melt inclusions or supercritical fluid inclusions [32–38]. Such inclusions have been one of key avenues to learn the nature of geologic processes operated within the interior of the Earth and the geochemical properties and behaviors, and the tectonophysical effects of deep fluids or melts. Bureau and Keppler [32] reported silicate-rich melt inclusions coexist with fluid inclusions in spinel lherzolites, which indicates the presence of supercritical fluids rich in water and silicate in the mantle. Upon pressure drops, such supercritical fluids unmix and form the silicate-rich melt inclusions and fluid inclusions. Diamonds from kimberlites and UHP calc-silicates also contain Si-rich melt inclusions with up to 67 wt% SiO_2 and 12 wt% K_2O [33,34]. In diamond-bearing UHP rocks from Kokchetav, water-rich inclusions were found in both diamond and clinopyroxene [35]. These observations show that melts or supercritical fluids rich in K, Na, and Si serve as excellent medium for the growth of diamond under UHP conditions [36–38].

In the presence of H_2O -rich fluid, K-feldspar is not stable at pressure greater than 2.5 GPa and will transform into K-cymeryte [12,39,40]. In addition, hydrous granitic melts with H_2O content of c. 10 wt% should occur at the estimated peak metamorphic conditions for the Sulu UHP eclogite ($P>3.3$ GPa and $T=750\text{--}850^\circ\text{C}$) [11,12], implying the high potential in forming K-cymeryte in the Dabie-Sulu UHP rocks under UHP conditions. By careful examination of K-bearing polyphase inclusions in the Sulu eclogites, Zeng et al. [31] found remnant K-cymeryte in such inclusions, which suggests that at least part of these quartzo-feldspathic inclusions had experienced K-cymeryte to K-feldspar phase transformation and should be formed under UHP conditions, consistent with results from experiments and theoretical modeling [11,12,41]. Except for the volume increase due to coesite→quartz and K-cymeryte→K-feldspar phase transformation, dehydration of hydrous granitic melt inclusions within the UHP rocks also contribute to various degrees of volume changes during the rapid exhumation of UHP rocks. With decrease in water contents, hydrous melt inclusions should increase their volume to maintain their liquid state, and in turn could enhance brittle deformation in their hosts. This process could be one of the important factors that lead to the formation of radial fractures or off-shoot structures around the hosts for the quartzo-feldspathic inclusions.

Studies on the composition of fluid inclusions in the Sulu eclogites have shown that salt-bearing fluid inclusions formed under UHP conditions are dominantly of $\text{NaCl}\text{--}\text{CaCl}_2\text{--}\text{H}_2\text{O}$ [19,21–23]. Such compositions are substantially deviated from $\text{KCl}\text{--}\text{NaCl}$ of solid salt within the quartzo-feldspathic inclusion reported in this study, implying different formation mechanisms. The solubility of H_2O and CO_2 in silicate melts is low [42], once the pressure drops below the second critical end point, fluid and melt unmix and form fluid and melt separately. It is conceivable that NaCl and KCl dissolved in the immiscible fluids should increase during progressive reaction of melt with quartz (or coesite) or other phases. Such fluids precipitate $\text{KCl}\text{--}\text{NaCl}$ crystals during dehydration and desiccation within these quartzo-feldspathic inclusions. In silicate melts, Cl present as complexes of alkaline elements (K and Na) with Cl ions. Aqueous fluids in equilibrium with silicate melts are enriched in Cl, but the partitioning behavior of Cl between aqueous fluids and silicate melts depends on the chemical composition and concentration of Cl in the silicate melt [43]. Therefore, during the degassing of high-Si melts, Cl will strongly partition into aqueous fluids and lower the Cl concentration in the coexisting melts. Experiments have already shown that NaCl and KCl salt form solid solution in relatively lower pressure rocks [44]. Solid NaCl and KCl salt inclusions were reported in high pressure granulite facies rocks [45,46]. Such solid salt inclusions represent products from sequential hydration, dehydration and desiccation, and concentration of Cl in granulite facies rocks. During granulite facies metamorphism, short and transient hydration re-

sulted in the formation of Cl-bearing aqueous fluids, subsequent dehydration and desiccation concentrate Cl and produced hydrous fluids rich in Cl as well as Cl-bearing hornblende and biotite; these Cl-concentrated aqueous fluids underwent further dehydration and desiccation and ultimately resulted in the solid salt inclusions in these granulite facies rocks [45]. In the Sulu eclogites, coexisting of solid salt with K-feldspar, albite, and quartz suggests that these K-feldspar-bearing inclusions might have experienced similar processes. Silicate melts or supercritical fluids captured by either garnet or omphacite had undergone crystallization and desiccation and generated associations of quartzo-feldspathic inclusion \pm solid salt inclusion \pm barite as pressure dropped during rapid exhumation of UHP rocks.

Polyphase inclusions consisting of hydrous, Ti-bearing and P-bearing minerals in HP to UHP phases in the eclogites from Donghai, Jiangsu Province, indicated the presence of supercritical fluids at UHP conditions or at the earliest stages of rapid exhumation [16,47]. Liu et al. [48] found Cl-bearing hornblende in the Sulu eclogite and interpreted that they were formed from aqueous fluids rich in Cl produced by hydration of phengite and normally anhydrous minerals (NAM) (e.g. garnet, omphacite, and rutile) during the transition from eclogite facies to amphibolite facies metamorphism. Cluster of fluid inclusions enriched in salt components in the core of garnets in the Sulu UHP eclogites were also documented by Shen et al. [22]. Such fluid inclusions are characterized by very high density and were captured under the quartz eclogite facies conditions (820°C, 2.4 GPa) [22]. These studies together with this new observation demonstrated that fluids rich in Cl were present at different metamorphic stages and could have regulated the chemical behaviors of key phases in the Sulu UHP eclogites.

Among quartzo-feldspathic inclusions reported in previous studies, some contain barite [5,16], while others contain zircon [27]. One of the inclusions (MS-1) in this contribution contains epidote. Such epidote could be produced either by reaction of granitic melt with the host omphacite (Reaction 1) or by crystallization directly from the melt (Reaction 2). In the inclusion MS-1, epidotes consist of mainly FeO and negligible MgO (Table 1), in contrast, their host omphacite consists of ~9.0 wt% MgO and 4.6 wt%–4.7 wt% FeO. If these epidotes were resulted from melt-omphacite reactions, then these epidotes should contain a large amount of MgO, which is not observed. In addition, epidote occurs neither in the constituent phases (e.g. garnet, omphacite and rutile) nor in the symplectite. Both lines of evidence argue against Reaction 1 as a viable mechanism for the presence of epidote in the inclusion MS-1. Therefore, epidotes in the inclusion MS-1 should represent products directly derived from the granitic melt, which in turn implies that such melts should be hydrous and contain a substantial amount of Fe and Ca. Overall, these special polyphase inclusions indicate the presence of silicate melts rich in volatile components under UHP conditions in the UHP rocks.

Titanite is commonly observed as retrograde product from rutile in many eclogites that have experienced amphibolite facies retrograde reactions. Presence of titanite in these polyphase inclusions seems that they were derived from retrograde breakdown of rutile. However, two lines of observation preclude such a possibility. First, in sample CCSD-02, rutile grains are intact and do not experience rutile-titanite transformation. Second, no titanite occurs either in the symplectites or in the retrograde veinlets. Therefore, presence of titanite in these inclusions signifies enhanced solubility of Ti in Cl-bearing granitic melts or supercritical fluids. Such an inference is supported by recent experimental results demonstrating that solubility of rutile in Cl-bearing fluids is increased by 2–4 times higher than that in ordinary aqueous fluids [25], and up to ~5000 ppm of Ti in supercritical NaAlSi₃O₈-H₂O fluids [49]. With the presence of Cl-bearing granitic melts or supercritical fluids as represented by the polyphase inclusions in the Sulu eclogites, it is conceivable that rutile solubility should be substantially enhanced and elevated amounts of Ti and other elements with similar geochemical affinity could be released into the melt or fluid. Consequently, these melts or fluids mobilize Ti and other HFSE and crystallized titanite together with quartzo-feldspathic phases in response to dehydration and desiccation. In summary, quartzo-feldspathic melts presented during the subduction and exhumation of UHP rocks serve as an important medium to transport both fluid-mobile (LILE and LREE) and -immobile (HFSE) elements, and impart strong effects on the geochemistry of the overlying wedge and subducting slab itself [50]. Partial melting in deeply subducted continental slab may be a major factor that contributes to rapid exhumation of UHP rocks by changing the geophysical properties of the slab.

We thank Prof. Yong-Fei Zheng and Drs. Xiaoying Gao and Yixiang Chen for discussion and valuable comments in preparing the manuscript. We also thank two reviewers for providing thoughtful comments that enable us to clarify our interpretations. This work was supported by the SinoProbe Project (SinoProbe-2-6) and the National Natural Science Foundation of China (41073024 and 40872048).

- 1 Ye K, Cong B, Ye D. The possible subduction of continental material to depths greater than 200 km. *Nature*, 2000, 407: 734–736
- 2 Chopin C. Ultrahigh-pressure metamorphism: tracing continental crust into the mantle. *Earth Planet Sci Lett*, 2003, 212: 1–14
- 3 Zheng Y F. Fluid regime in continental subduction zones: Petrological insights from ultrahigh-pressure metamorphic rocks. *J Geol Soc Lond*, 2009, 166: 763–782
- 4 Zheng Y F, Gong B, Li Y, et al. Carbon concentrations and isotopic ratios of eclogites from the Dabie and Sulu terranes in China. *Chem Geol*, 2000, 168: 291–305
- 5 Zeng L S, Liu F L, Liang F H, et al. Barite in omphacite-hosted K-feldspar + quartz polycrystalline aggregates from the Sulu eclogites and its implications. *Chin Sci Bull*, 2007, 52: 2995–3001
- 6 Huang W L, Wyllie P J. Phase relationships of S-type granite with H₂O to 35 kbar: Muscovite granite from Harney Peak, South Dakota. *J Geophys Res*, 1981, 86: 10515–10529
- 7 Nichols G T, Wyllie P J, Stern C R. Subduction zone melting of pelagic sediments constrained by melting experiments. *Nature*, 1994,

- 371: 785–788
- 8 Patiño Douce A E, McCarthy T C. Melting of crustal rocks during continental collision and subduction. In: Hacker B R, Liou J G, eds. *When Continents Collide: Geodynamics and Geochemistry of Ultra-high-Pressure Rocks*. Dordrecht: Kluwer Academic Publishing, 1998. 27–55
 - 9 Schmidt M W. Experiment constraints on recycling of potassium from subducted oceanic crust. *Science*, 1996, 272: 1927–1930
 - 10 Holloway J R, Domanik K J. Experimental synthesis and phase relations of phengitic muscovite from 6.5 to 11 GPa in a calcareous metapelite from the Dabie Mountains, China. *Lithos*, 2000, 52: 51–77
 - 11 Hermann J, Green D H. Experimental constraints on high pressure melting in subducted crust. *Earth Planet Sci Lett*, 2001, 188: 149–168
 - 12 Hermann J. Experimental constraints on phase relations in subducted continental crust. *Contrib Mineral Petrol*, 2002, 143: 219–235
 - 13 Schmidt M W, Vielzeuf D, Auzanneau E. Melting and dissolution of subducting crust at high pressures: The key role of white mica. *Earth Planet Sci Lett*, 2004, 228: 65–84
 - 14 Auzanneau E, Vielzeuf D, Schmidt M W. Experimental evidence of decompression melting during exhumation of subducted continental crust. *Contrib Mineral Petrol*, 2006, 152: 125–148
 - 15 Hermann J, Spandler C J. Sediment melts at sub-arc depths: An experimental study. *J Petrol*, 2008, 49: 717–740
 - 16 Zheng Y F, Xia Q X, Chen R X, et al. Partial melting, fluid supercriticality and element mobility in ultrahigh-pressure metamorphic rocks during continental collision. *Earth-Sci Rev*, 2011, 107: 342–374
 - 17 Kessel R, Schmidt M W, Ulmer P, et al. Trace element signature of subduction-zone fluids, melts and supercritical liquids at 120–180 km depth. *Nature*, 2005, 437: 724–727
 - 18 Hermann J, Spandler C, Hack A, et al. Aqueous fluids and hydrous melts in high-pressure and ultra-high pressure rocks: Implications for element transfer in subduction zones. *Lithos*, 2006, 92: 399–417
 - 19 Xiao Y L, Hoefs J, van den Kerkhof A M, et al. Fluid evolution during HP and UHP metamorphism in Dabie Shan, China: Constraints from mineral chemistry, fluid inclusions and stable isotopes. *J Petrol*, 2002, 43: 1505–1527
 - 20 Fu B, Touret J L R, Zheng Y F. Fluid inclusions in coesite-bearing eclogites and jadeite quartzite at Shuanghe, Dabie Shan, China. *J Meta Geol*, 2001, 19: 529–545
 - 21 Shen K, Zhang Z M, van den Kerkhof A M, et al. Unusual high-density and saline aqueous inclusions in ultra-high pressure metamorphic rocks from Su-Lu terrane, in eastern China. *Chin Sci Bull*, 2003, 48: 2018–2023
 - 22 Shen K, Zhang Z M, Huang T L, et al. Study of fluid inclusions in zircons of UHP metamorphic rocks from the main drillhole of the Chinese Scientific Drilling Project (CCSD). *Acta Petrol Sin*, 2006, 22: 1975–1984
 - 23 Zhang Z M, Shen K, Sun W D, et al. Fluids in deeply subducted continental crust: petrology, mineral chemistry and fluid inclusion of UHP metamorphic veins from the Sulu orogen, eastern China. *Geochim Cosmochim Acta*, 2008, 72: 3200–3228
 - 24 Zheng Y F, Fu B, Gong B, et al. Stable isotope geochemistry of ultrahigh pressure metamorphic rocks from the Dabie-Sulu orogen in China: Implications for geodynamics and fluid regime. *Earth-Sci Rev*, 2003, 62: 105–161
 - 25 Rapp J F, Klemme S, Butler I B, et al. Extremely high solubility of rutile in chloride and fluoride-bearing metamorphic fluids: An experimental investigation. *Geology*, 2010, 38: 323–326
 - 26 Yang J, Godard G, Smith D C. K-feldspar-bearing coesites pseudomorphs in an eclogite from Lanshantou (Eastern China). *Eur J Mineral*, 1998, 10: 969–985
 - 27 Zeng L S, Liang F H, Asimow P, et al. Partial melting of deeply subducted continental crust and the formation of quartz-feldspathic polyphase inclusions in the Sulu UHP eclogites. *Chin Sci Bull*, 2009, 54: 2580–2594
 - 28 Gao X Y, Zheng Y F, Chen Y X. Dehydration melting of ultra-high-pressure eclogite in the Dabie orogen: Evidence from multiphase solid inclusions in garnet. *J Meta Geol*, 2012, 30: 193–212
 - 29 Liang F H, Zeng L S, Chen J, et al. Discovery of apatite with copper-bearing pyrrhotite exsolution in an eclogite from Rongcheng, eastern Shandong Province. *Acta Petrol Sin*, 2006, 22: 433–438
 - 30 Chen J, Zeng L S, Chen F Y, et al. 2006. Preliminary studies on the Qinglongshan apatites with sulfide solid exsolution. *Acta Petrol Sin*, 2006, 22: 1921–1926
 - 31 Zeng L S, Chen J, Chen Z Y, et al. K-cymrite in the Sulu UHP eclogites. *Acta Petrol Sin*, 2009, 25: 2141–2148
 - 32 Bureau H, Keppler H. Complete miscibility between silicate melts and hydrous fluids in the upper mantle: Experimental evidence and geochemical implications. *Earth Planet Sci Lett*, 1999, 165: 187–196
 - 33 Navon O, Hutcheon I D, Rossman G R, et al. Mantle-derived fluids in diamond micro-inclusions. *Nature*, 1988, 335: 784–789
 - 34 Korsakov A V, Hermann J. Silicate and carbonate melt inclusions associated with diamonds in deeply subducted carbonate rocks. *Earth Planet Sci Lett*, 2006, 241: 104–118
 - 35 Ogasawara Y. Microdiamonds in ultrahigh-pressure metamorphic rocks. *Elements*, 2005, 1: 91–96
 - 36 Hwang S L, Shen P, Chu H T, et al. Genesis of microdiamonds from melt and associated multiphase inclusions in garnet of ultrahigh-pressure gneiss from Erzgebirge, Germany. *Earth Planet Sci Lett*, 2001, 188: 9–15
 - 37 Stöckhert B, Duyster J, Trepman C, et al. Microdiamond daughter crystals precipitated from supercritical CO₂ + silicate fluids induced in garnet, Erzgebirge, Germany. *Geology*, 2001, 29: 391–394
 - 38 Palyanov Y N, Shatsky V S, Sobolev N V, et al. High-Pressure Geoscience Special Feature: The role of mantle ultrapotassic fluids in diamond formation. *Proc Natl Acad Sci USA*, 2007, 104: 9122–9127
 - 39 Thompson P, Parsons I, Graham C M, et al. The breakdown of potassium feldspar at high water pressure. *Contrib Mineral Petrol*, 1998, 130: 176–186
 - 40 Hwang S L, Shen P, Chu H-T, et al. Kokchetavite: A new potassium-feldspar polymorph from the Kokchetav ultrahigh-pressure terrane. *Contrib Mineral Petrol*, 2004, 148: 380–389
 - 41 Yang J J, Powell R. Calculated phase relations in the system Na₂O–CaO–K₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O with applications to UHP eclogites and whiteschists. *J Petrol*, 2006, 47: 2047–2071
 - 42 Frost B R, Frost, C D. CO₂, melts and granulite metamorphism. *Nature*, 1987, 327: 503–506
 - 43 Metrich N, Rutherford M J. Experimental study of chlorine behavior in hydrous silicic melts. *Geochim Cosmochim Acta*, 1992, 56: 607–616
 - 44 Thompson Jr J B, Waldbaum D R. Analysis of the two-phase region halite-sylvite in the system NaCl–KCl. *Geochim Cosmochim Acta*, 1969, 33: 671–690
 - 45 Markl G, Bucher K. Composition of fluids in the lower crust inferred from metamorphic salt in lower crustal rocks. *Nature*, 1998, 391: 781–783
 - 46 Trommsdorf V, Skippen G, Ulmer P. Halite and sylvite as solid inclusions in high-grade metamorphic rocks. *Contrib Mineral Petrol*, 1985, 89: 24–29
 - 47 Ferrando S, Frezzotti M L, Dallai L, et al. Multiphase solid inclusions in UHP rocks (Su-Lu, China): Remnants of supercritical silicate-rich aqueous fluids released during continental subduction. *Chem Geol*, 2005, 223: 68–81
 - 48 Liu J B, Liu W Y, Ye K, et al. Chlorine-rich amphibole in Yangkou eclogite, Sul ultrahigh-pressure metamorphic terrane, China. *Eur J Mineral*, 2009, 21: 1265–1285
 - 49 Hayden L A, Manning C E. Rutile solubility in supercritical NaAlSi₃O₈–H₂O fluids. *Chem Geol*, 2011, 284: 74–81
 - 50 Zhao Z F, Zheng Y F, Chen R X, et al. Element mobility in mafic and felsic ultrahigh-pressure metamorphic rocks during continental collision. *Geochim Cosmochim Acta*, 2007, 71: 5244–5266